

The Optical Gravitational Lensing Experiment*. Difference Image Analysis of LMC and SMC Data. The Catalog

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ABSTRACT

We present the first edition of a catalog of variable stars found in the Magellanic Clouds using OGLE-II data obtained during four years: 1997–2000. The catalog covers about 7 square degrees of the sky – 21 fields in the Large Magellanic Cloud and 11 fields in the Small Magellanic Cloud. All variables were found with the Difference Image Analysis (DIA) software. The catalog is divided into two sections. The DC section contains FITS reference images (obtained by co-adding 20 best frames for each field) and profile photometry (DoPHOT) of all variable stars on those images. The AC section contains flux variations and magnitudes of detected variable stars obtained with DIA as well as with DoPHOT. The errors of magnitude measurements are 0.005 mag for the brightest stars ($I < 16$ mag) then grow to 0.08 mag at 19 mag stars and to 0.3 mag at 20.5 mag. Typically, there are about 400 I -band data points and about 30 V and B -band data points for more than 68 000 variables. The stars with high proper motions were excluded from this catalog and will be presented in a separate paper. A detailed analysis and classification of variable stars will be presented elsewhere. The catalog is available in electronic form *via* FTP and through WWW interface from the OGLE Internet archive. The FTP catalog contains approximately 2 GB of data.

Magellanic Clouds – Catalogs – Stars: variables: general

1 Introduction

The second phase of the Optical Gravitational Lensing Experiment (OGLE-II) spans four years, from 1997 to 2000. The main goal of the project was the search for microlensing events, but a natural by-product after four years of observations is a huge database of photometric measurements for millions

*Based on observations obtained with the 1.3-m Warsaw telescope at Las Campanas Observatory of the Carnegie Institution of Washington.

of objects. Currently, the third phase of the project (OGLE-III) is underway. In this paper we present the catalog of variable stars in the Magellanic Clouds found in the already closed dataset of OGLE-II.

In previous papers the OGLE collaboration published *BVI*Maps of the Small Magellanic Cloud (Udalski *et al.* 1998a) and the Large Magellanic Cloud (Udalski *et al.* 2000), catalogs of Cepheids in the LMC (Udalski *et al.* 1999a) and SMC (Udalski *et al.* 1999b) and catalog of Eclipsing Binary Stars in the SMC (Udalski *et al.* 1998b).

This paper describes the catalog of all variable objects found in the Magellanic Clouds with the Difference Image Analysis (DIA) package – an implementation of Alard and Lupton (1998) optimal Point Spread Function (PSF) matching algorithm (Woźniak 2000). The stars presented in the catalog represent numerous types of variability. The full details of the DIA software can be found in papers by Woźniak (2000, hereafter Paper I) and by Źebruń, Soszyński and Woźniak (2001, hereafter Paper II). We emphasize, that this is the first, preliminary, edition of the catalog, which may contain some spurious variables, and some genuine variables might have been missed.

2 Observational Data

The photometric data were collected with the 1.3-m Warsaw telescope located at the Las Campanas Observatory, Chile. The telescope was equipped with the "first generation" camera with the SITE 2048×2048 CCD detector working in the driftscan mode. The pixel size was $24 \mu\text{m}$ giving the 0.417 arcsec/pixel scale. Observations of the LMC were performed in the "slow" reading mode of the CCD detector with the gain $3.8 \text{ e}^-/\text{ADU}$ and readout noise about 5.4 e^- . Details of the instrumentation setup can be found in Udalski, Kubiak and Szymański (1997).

Regular observations of the LMC fields started on January 6, 1997, while observations of the SMC started on June 26, 1997. About 4.5 square degrees of central parts of the LMC and about 2.4 square degrees of the SMC were observed during four seasons. In this catalog we present data collected up to the end of May 2000. The DIA photometry is based on the *I*-band observations. The total number of photometric measurements for about 2×10^7 stars exceeded 6×10^9 . The mean seeing of the collected data is $1.^{\prime\prime}34$. Fig. 1. shows the histogram of the seeing data.

The second edition of the catalog will include observations collected up to the end of November 2000, when OGLE-II phase was concluded.

3 The Catalog

There is a trade-off between the amount of time allocated to the preparation of a catalog and the quality of the product. Given practical limitations we decided to present a catalog which is preliminary rather than final. We are just entering

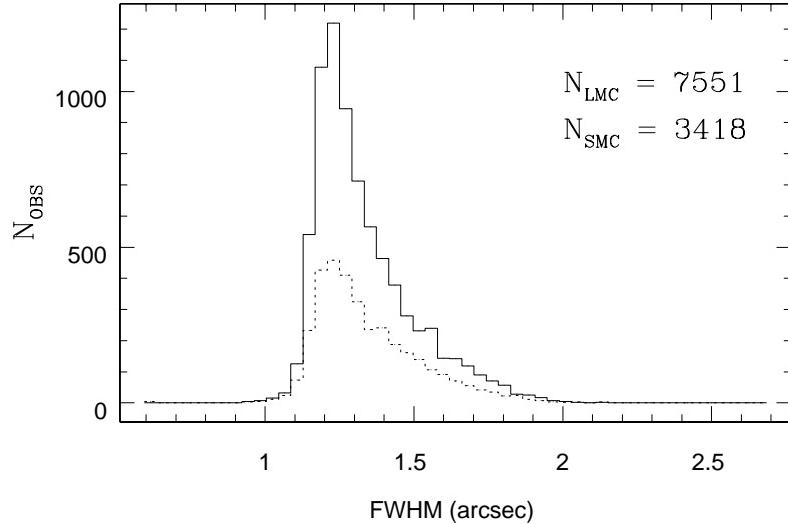


Fig. 1. The histogram of seeing of all individual OGLE II observations of the Magellanic Clouds. 7551 observations of 21 LMC fields (solid line) and 3418 observations of 11 SMC fields (dashed line) were used. The bin size is 0.041 arcsec, corresponding to 0.1 pixel on CCD image. The mean FWHM value is 1.''34 arcsec for both the LMC and SMC.

the era of Tera Byte sized datasets, and it seems that results of such big projects will take an evolving form. We intend to correct in the future editions whatever deficiencies will be found in the current catalog.

Because the dataset obtained with the DIA method is very large, we decided to make this data available only in the electronic form. Below we describe contents of our catalog, and in the next Section we present brief instructions on how to use the catalog. The catalog contains more than 68 000 *I*-band light curves for variable objects found among almost 17×10^6 objects detected in the LMC and SMC. The magnitudes of stars are transformed to the standard system (Udalski *et al.* 2000). The errors of magnitude measurements are 0.005 mag for the brightest stars ($I < 16$ mag) then grow to 0.08 mag at 19 mag stars and to 0.3 mag at 20.5 mag.

Table 1 presents a summary of observations, which we used to create the catalog. The consecutive columns give the field name, the number of *I*-band measurements N_I , the number of variable stars N_{var} , the total number of stars found on reference images N_{total} by standard DOPHOT routine, and the equatorial coordinates of the field centers for the epoch 2000. The details of the method used to create reference frames and to obtain photometry presented in this catalog can be found in Paper I and Paper II.

The DIA package measures separately DC (constant signal) flux and AC (variable signal) flux for every variable object. Therefore we decided to divide the catalog into two parts, DC and AC, which can be accessed independently. In the DC part we included the FITS files of all *I*-band reference images for 21 LMC and 11 SMC fields. For each field there is a single 2048×8192 image of

whole field and 256 images of 512×128 subframes as well. This partitioning of the original image and the specific size of the subframes reflects the fact that we had to minimize PSF variations along whole image (see Paper I).

One can also find the results of DoPHOT photometry run on the DIA reference image (DIA DoPHOT) and the file with zero points for each subframe. Transformation between the DIA flux and DoPHOT magnitudes gives only the instrumental magnitude, which has to be shifted to match the standard photometric system. Note that files with DIA DoPHOT photometry are not zero point corrected. The format of a DoPHOT file is shown below:

2	301.48	15.24	-12.370	0.007	409.595
3	183.83	77.00	-12.932	0.007	401.944
4	201.42	88.27	-12.184	0.007	407.488
5	59.35	11.97	-11.724	0.005	426.509

The columns mean: star number, x coordinate, y coordinate, magnitude, error, background. One must remember that the DIA DoPHOT photometry is obtained on a image that is a sum of twenty images. This photometry is intended to be used only as reference for DIA. The star x coordinate ranges from 0 to 2048 pixels while y coordinate – from 0 to 8192 pixels.

The zero point file is presented in the format: X section number, Y section number, zero point value, *i.e.*, :

1	1	26.685
2	1	26.669
3	1	26.659

The sections number range from 1 to 4 in x coordinate and from 1 to 64 in y coordinate.

We also provide a table with a single row for any variable object in the following sequence:

- name of the variable, we are using convention OGLE $hhmmss.ss-ddmmss.s$ *e.g.*,: OGLE050129.81–683647.0, where the name gives the coordinates: RA = $05^{\text{h}}01^{\text{m}}29^{\text{s}}81$, DEC = $-68^{\circ}36'47''0$,
- RA and DEC coordinates, these coordinates are written as $hh:mm:ss.ss dd:mm:ss.s$ and as decimal values,
- the x and y pixel coordinates of a star on the reference frame; these are coordinates produced by DIA package, they refer to the position of a variable object and therefore may be somewhat different from the position of a star detected by DoPHOT on the reference frame,
- the X and Y number of the subsection containing the star,
- DIA profile and aperture photometry with errors,
- the number of I -band frames used in DIA, *i.e.*, the total number of I -band OGLE observations of a given object,
- the number of I , V and B -band data from OGLE databases,
- the data for the closest star identified by DoPHOT on the DIA reference frame – number of the star given by DoPHOT, distance to this star (pixels), its magnitude and error,

- the data for the closest star identified on the OGLE template – number of the star in the OGLE database, distance to this star (pixels), its mean magnitude and error,
- the last column contains additional flags and remarks.

Below there is a sample table row. Because of its length, it is presented as three lines.

OGLE052957.63-702005.8	5:29:57.63	-70:20:05.8	5.499342	70.334944
60.154	11.775	1 1	4530.2812	21.5921
282	49	0 5	0.827	15.071
			0.005	20 0.819
				15.124 0.058 0

The data included in the above list are also presented in the WWW part of the on-line catalog.

The AC catalog contains the DIA data for variable objects. The description of the databases can be found in Paper I and Paper II. This set of variable objects contains stars presenting numerous types of variability, *i.e.*, pulsating, eclipsing, flare, RCB stars, etc. Several examples of light curves are shown in Figs. 2, 3 and 4. At this time we do not attempt to classify the types of these variables.

The catalog is only weakly filtered and even though many of the artifacts were removed (*cf.* Section 7 of Paper II) many of them are still present. To help the reader to find the stars that are uncertain we marked them as uncertain in the list of variable objects.

Our classification criterion was very simple. For each star we calculated number of good measurements in flux (N_{flux}). We did the same for magnitude (N_{mag}) but only measurements inside 12–19.5 mag limits[†] were taken into account. Then we calculated mean magnitude of the star, σ of all measurements and number of measurements over $+5\sigma$ ($N_{5\sigma}$) and $+10\sigma$ limit ($N_{10\sigma}$) above mean magnitude. The star was treated as uncertain when N_{mag} was less than $N_{\text{flux}}/2$ and when $N_{5\sigma}$ and $N_{10\sigma}$ were less than 10 or 3 respectively. The uncertain stars are marked in the catalog as uncertain. We left to the reader the final judgment whether the variable star is real or it is only an artifact.

The AC catalog light curves are presented in flux and magnitude units. The transformation to magnitude system is described in Section 4 of Paper II. The linear flux light curves contain only the AC part of the signal.

The time vector contains Heliocentric Julian date (HJD) minus 2 400 000.0 and the time corresponds to the beginning of the driftscan. One has to remember that in the driftscan mode the mid-exposure time is different for objects located in different parts of the image. For a given object the mid-exposure time can be found with accuracy to a few seconds by adding a correction Δt :

$$\Delta t = (y + 1024) \times 0.060776 / 86400 \quad [\text{days}]$$

where y is the coordinate of the object in the reference image.

[†]The 12 mag limit is the typical saturation level for OGLE-II data, while the 19.5 mag limit is subjectively chosen threshold below which measured magnitudes become uncertain.

For convenience the DIA *I*-band measurements expressed in magnitudes have the zero point of DC signal added. They were also calibrated to standard system using relations derived for the OGLE data (Udalski *et al.* 1998a, 2000). For comparison purposes we also supplemented the AC part of the catalog with the regular OGLE DoPHOT photometry in *I*, *V* and *B*-band for objects that are best identified with the DIA variable star positions.

The measurements of AC signal presented in the catalog are very precise. However this statement is not true for the DC flux measurement on a reference image. Depending on distance of cross-identification of a variable candidate from DIA with DIA DoPHOT positions of stars we decided to use DIA DoPHOT DC signal or DIA DC signal. The DIA DoPHOT DC flux is affected by the fact that the positions of variable objects returned by DIA are often positions of blends of stars detected by DIA DoPHOT. The DIA DC flux is also affected because DIA is not modeling the star's vicinity on a reference frame and not removing nearby stars prior to calculating the flux. This makes the correct measurement of a DC signal a serious problem. Currently the OGLE-III phase of the OGLE project is underway. With better spatial resolution than available in OGLE-II, we will be able to extract more precise signal with both DoPHOT and DIA photometry. For details about DC flux measurement we refer to Section 5 in Paper II.

4 How to Use the Catalog

The catalog is available on-line through FTP and WWW from the OGLE Internet archive. Here we present a brief instructions for users.

4.1 The Catalog Through FTP

The catalog that can be accessed *via* anonymous ftp at the following addresses:

```
ftp://bulge.princeton.edu/ogle/ogle2/dia/
ftp://sirius.astrowu.edu.pl/ogle/ogle2/dia/
```

The catalog is placed in two subdirectories *dc/* and *ac/* containing data for DC and AC signal respectively. Below we summarize contents of these directories.

For the DC catalog there are the following directories:

- *dc/lmc/* and *dc/smc/* – the DIA reference images: 16 MB gzip compressed FITS images of the whole fields,
- *dc/lmc_scN/* or *dc/smc_scN/* where *N* means the field number; these are the reference images stored as 256 FITS images of subsections; the name of a single gzip compressed file is *ref_X_Y.fts.gz*, where *X* and *Y* are the location of the subframe within a 4×64 partition of the full frame,
- *dc/dia_dophot/* – DoPHOT photometry on the DIA reference image,
- *dc/zero_points/* – magnitude zero points for all fields (by sections),
- *dc/tables/* – text tables for all LMC and SMC fields (one row per variable, see the previous Section).

The AC catalog contains complete photometry for all variable stars. For convenience we compressed archived photometry for whole fields. The file names are *lmc_scN.tar.gz* and *smc_scN.tar.gz*. Individual photometry files for each variable are named using our new coordinate naming convention:

- *OGLEhhmmss.ss-ddmmss.s.flux* – AC signal in the DIA flux units,
- *OGLEhhmmss.ss-ddmmss.s.mag* – magnitude light curves, with DC signal and zero point added.

The AC section of the catalog available through FTP fills approximately 0.4 GB of disk space and DC section approximately 1.6 GB.

4.2 The Catalog Through World Wide Web Page

We also created a WWW user interface. The catalog may be updated in the future, but the general form of data access will remain similar. The whole interface is prepared in such a way that expansions and modifications do not influence the availability of the catalog. The WWW catalog allows one to get a considerable amount of data for each suspected variable, and it is available at the following addresses:

http://bulge.princeton.edu/~ogle/ogle2/dia/
http://sirius.astroww.edu.pl/~ogle/ogle2/dia/

The main WWW catalog page is divided into two frames. In the left frame there are links for easy browsing the remote parts of the catalog. The contents of the right panel depends on the current choice from the menu on the left. The WWW catalog has two major parts referred to as CONSTANT DATA and VARIABLE DATA.

By entering the CONSTANT DATA part, one loads a map with locations of the LMC and SMC fields. A click inside the contour of a given field, allows to access corresponding data from the DC catalog. An example of a single window for LMC_SC17 field is shown in Fig. 5. The reference frame is displayed at the center, with a white pane superimposed on this image. The numbers on the sides help to find a given subsection of the reference image. A click selects given subsection for a download. There are also text links to the remaining CONSTANT DATA as described in the FTP section.

In the VARIABLE part of the WWW catalog, the user can browse lists of the all suspected variable objects. The table (Fig. 6) contains: variable name, *x* and *y* coordinates as returned by the DIA, *I*-band magnitude of the closest star detected by DoPHOT on the reference image and distance to this star. This distance is frequently larger than its expected error because the variable found using DIA is typically blended on the frame used for DoPHOT photometry.

The name of the variable is also a link, which takes the user to a window with additional information about the star. Fig. 7 shows the outlook of the window in the VARIABLE DATA part. The table in the upper part of the window contains coordinates of the star and information about stars that were closely identified on the DIA reference frame and in the OGLE database. A finding

chart and light curve of the object are created dynamically. If needed straight lines marking 12 mag and 19.5 mag limits are also plotted (see Section 3). The size of the finding chart (part of the deep reference image) is 168×168 pixels, corresponding to $70'' \times 70''$ on the sky. The North is up and East is to the left. In the right panel, the file with photometry is displayed. One can choose between the DIA I -band flux and magnitude units, and the OGLE I , V , B -band photometry.

5 Summary

The online catalog of OGLE-II candidate variables in the LMC and SMC from the DIA photometry contains light curves for more than 68 000 variable stars. Currently, it is a preliminary version which we expect to evolve towards a refined product, free of artifacts, more complete, with added complexity of scientific information like variability classes etc. The stars with high proper motions will be presented in a separate catalog. The main strengths of this work are precise differential photometry and very modest assumptions about included variability types, with the potential for finding new information on exotic objects discovered using other means or even the catalog itself. We encourage astronomers to make comments and propose improvements for the future versions.

Users can also obtain a copy of FTP catalog (approximately 2 GB) on a DAT tape. The request should be sent to Prof. B. Paczyński (bp@astro.princeton.edu).

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 Źebruń, K., Soszyński, I., and Woźniak, P.R. 2001, *Acta Astron.*, **51**, 303, (Paper II).

T a b l e 1
LMC and SMC fields observed by OGLE-II

Field	N_{obs}	N_{var}	N_{total}	RA	DEC
LMC_SC1	353	2146	633666	5 ^h 33 ^m 49 ^s	-70°06'10"
LMC_SC2	512	4620	702224	5 ^h 31 ^m 17 ^s	-69°51'55"
LMC_SC3	505	3993	738434	5 ^h 28 ^m 48 ^s	-69°48'05"
LMC_SC4	499	4128	781083	5 ^h 26 ^m 18 ^s	-69°48'05"
LMC_SC5	488	4032	760089	5 ^h 23 ^m 48 ^s	-69°41'05"
LMC_SC6	483	3964	785450	5 ^h 21 ^m 18 ^s	-69°37'10"
LMC_SC7	475	4060	767142	5 ^h 18 ^m 48 ^s	-69°24'10"
LMC_SC8	366	3277	706370	5 ^h 16 ^m 18 ^s	-69°19'15"
LMC_SC9	334	2774	655470	5 ^h 13 ^m 48 ^s	-69°14'05"
LMC_SC10	333	2250	596548	5 ^h 11 ^m 16 ^s	-69°09'15"
LMC_SC11	272	1920	579398	5 ^h 08 ^m 41 ^s	-69°10'05"
LMC_SC12	325	1558	488292	5 ^h 06 ^m 16 ^s	-69°38'20"
LMC_SC13	268	2729	551847	5 ^h 06 ^m 14 ^s	-68°43'30"
LMC_SC14	268	1494	478055	5 ^h 03 ^m 49 ^s	-69°04'45"
LMC_SC15	275	1535	455854	5 ^h 01 ^m 17 ^s	-69°04'45"
LMC_SC16	270	1813	541564	5 ^h 36 ^m 18 ^s	-70°09'40"
LMC_SC17	262	1523	484820	5 ^h 38 ^m 48 ^s	-70°16'45"
LMC_SC18	268	1371	430116	5 ^h 41 ^m 18 ^s	-70°24'50"
LMC_SC19	260	1068	420263	5 ^h 43 ^m 48 ^s	-70°34'45"
LMC_SC20	261	1442	421199	5 ^h 46 ^m 18 ^s	-70°44'50"
LMC_SC21	287	1417	447731	5 ^h 21 ^m 14 ^s	-70°33'20"
SMC_SC1	293	716	241836	0 ^h 37 ^m 51 ^s	-73°29'40"
SMC_SC2	283	1002	300524	0 ^h 40 ^m 53 ^s	-73°17'30"
SMC_SC3	276	1476	398790	0 ^h 43 ^m 58 ^s	-73°12'30"
SMC_SC4	299	1770	426827	0 ^h 46 ^m 59 ^s	-73°07'30"
SMC_SC5	313	2243	510928	0 ^h 50 ^m 01 ^s	-73°08'45"
SMC_SC6	308	2190	519334	0 ^h 53 ^m 01 ^s	-72°58'40"
SMC_SC7	273	1691	448674	0 ^h 56 ^m 00 ^s	-72°53'35"
SMC_SC8	285	1317	383912	0 ^h 58 ^m 58 ^s	-72°39'30"
SMC_SC9	279	1073	328343	1 ^h 01 ^m 55 ^s	-72°32'35"
SMC_SC10	273	665	274129	1 ^h 04 ^m 51 ^s	-72°24'45"
SMC_SC11	269	937	243914	1 ^h 07 ^m 45 ^s	-72°39'30"
Total:	10515	68194	16502826		

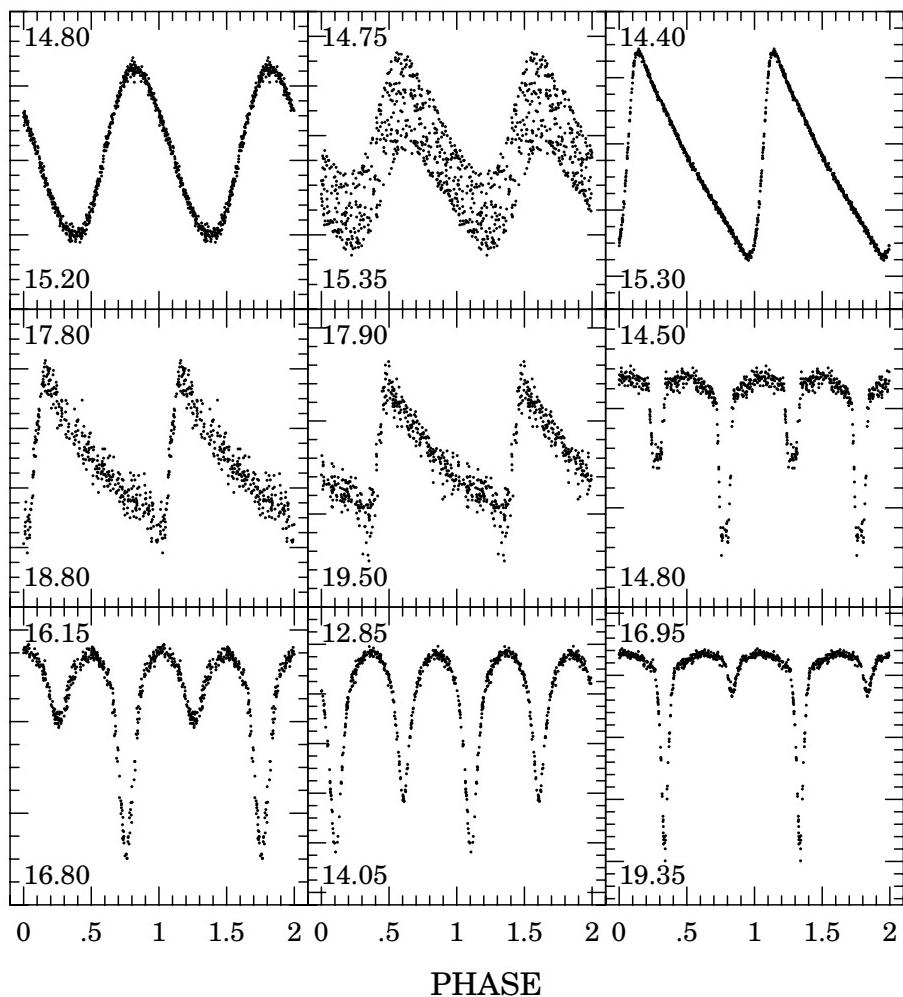


Fig. 2. Examples of DIA light curves of the LMC_SC2 pulsating and eclipsing stars.

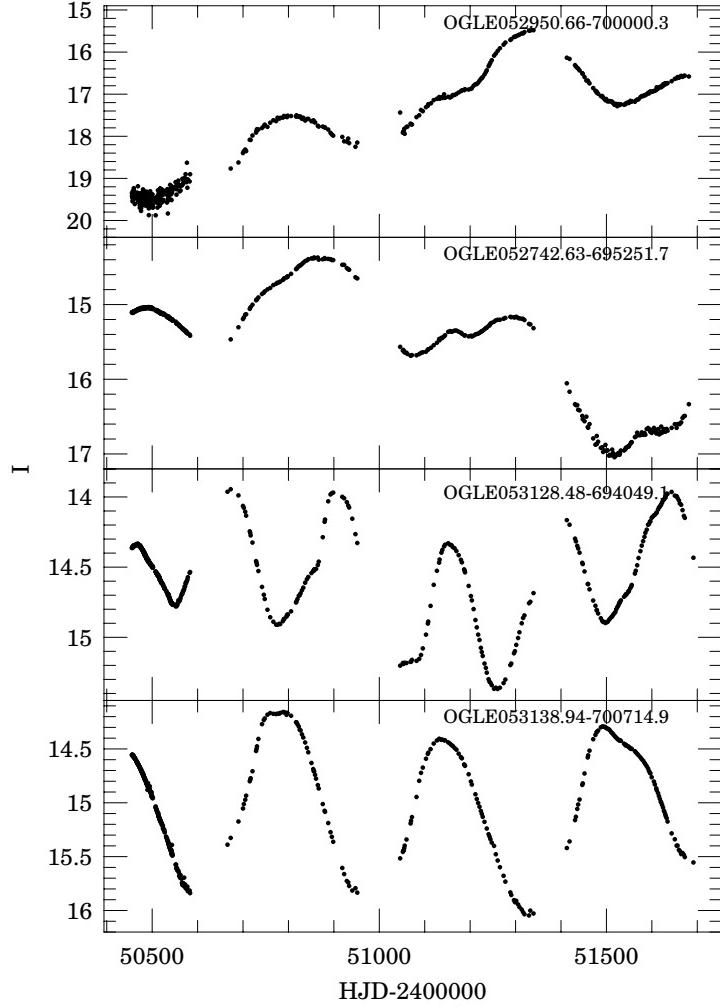


Fig. 3. Light curves of long period variables. The stars in the two upper panels are likely LPVs, while the stars in the two lower panels are good candidates for Mira variables.

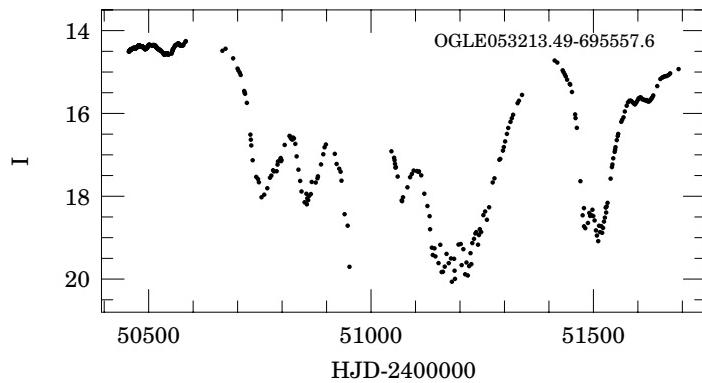


Fig. 4. OGLE053213.49-695557.6 – a candidate RCB variable. The light curve shows a quiescence period, a subsequent drop in magnitude, followed by long period of return to the quiescent magnitude.

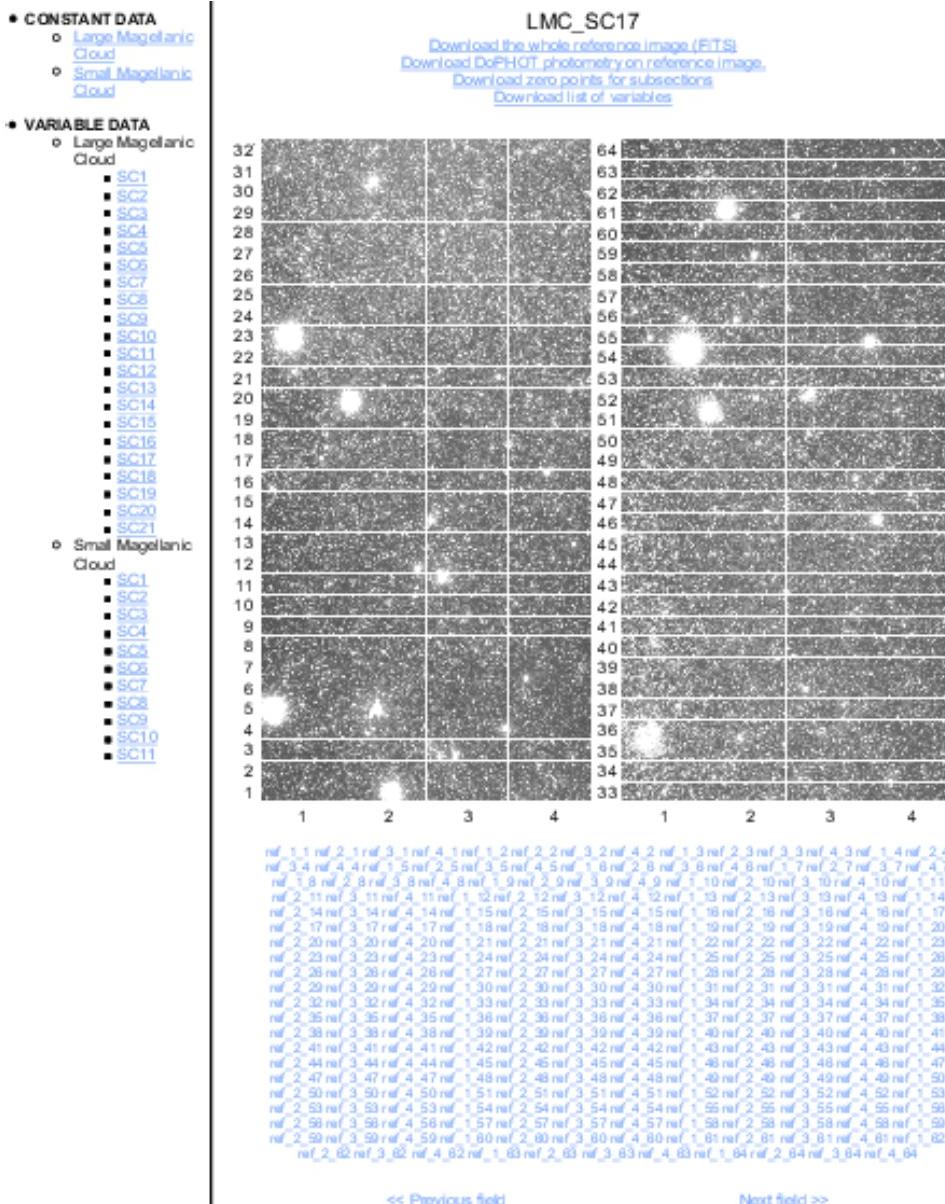


Fig. 5. CONSTANT (DC) DATA window in the on-line catalog. The left panel provides links for easy navigation of the VARIABLE (AC) and CONSTANT parts of the catalog. The right panel displays the DIA reference image. The pane on the image shows 512×128 pixel subsections in two strips. The user has a choice of downloading the entire reference image (FITS), or any of the subframes separately, using either text links or clickable image sections.

- **CONSTANT DATA**
 - Large Magellanic Cloud
 - Small Magellanic Cloud

- **VARIABLE DATA**
 - Large Magellanic Cloud
 - SC1
 - SC2
 - SC3
 - SC4
 - SC5
 - SC6
 - SC7
 - SC8
 - SC9
 - SC10
 - SC11
 - SC12

LMC_SC2

[Photometry of all variable stars in this field](#)

[<< Previous 100 variables](#) [Next 100 variables >>](#)

Var Name/Coordinates OGLEhhmmss.ss-ddmmss.s	X [pix.]	Y [pix.]	DIA				OGLE			I [mag]	dist. [pix.]	Remarks
			N _I	N _R	N _V	N _B						
OGLE053001.19-701248.8	96.313	1068.027	504	442	49	25	17.683	0.504				
OGLE053000.41-701248.7	86.625	1068.304	503	462	52	27	16.538	0.782				
OGLE053149.32-701247.5	1423.565	1074.421	507	430	54	26	14.777	0.117				
OGLE053205.49-701246.8	1621.956	1075.514	508	478	52	27	18.856	0.058				
OGLE053001.32-701245.2	97.737	1076.743	504	277	0	0	20.403	2.508				
OGLE053004.83-701244.2	140.829	1079.525	511	454	45	0	15.717	0.079	the same star in LMC_SC3			
OGLE053002.74-701242.5	115.201	1083.386	508	473	50	24	18.255	0.162				

Fig. 6. A screen shot of a star list from the AC part of the on-line catalog. The links to the DC and AC part of the catalog are in the left panel. In the right panel there is a table with a clickable list of variable stars. Each variable name provides a link to a new window with details about the star, see Fig. 7.

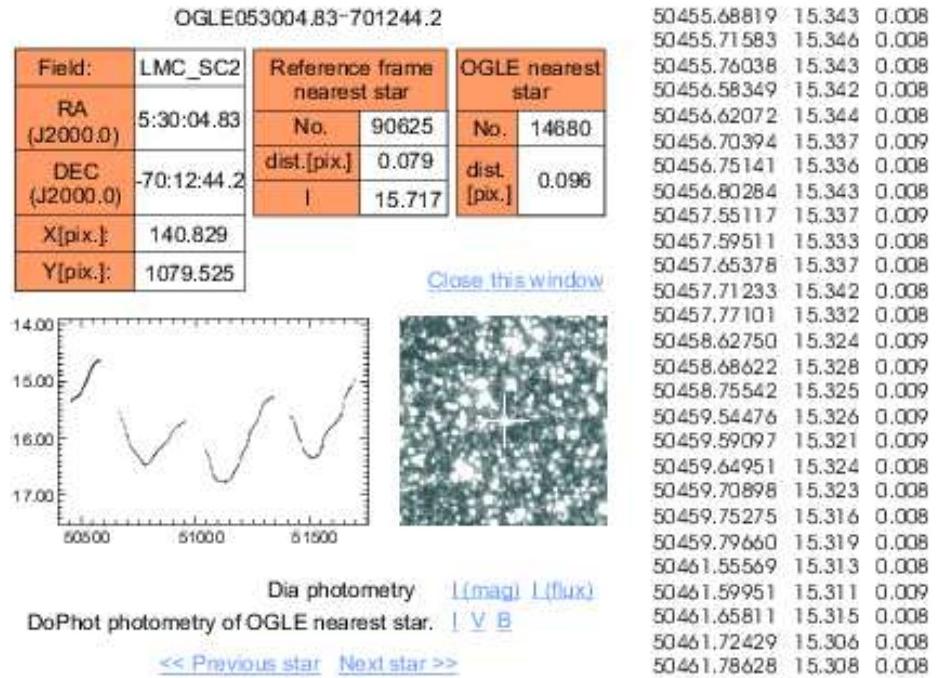


Fig. 7. A sample window with detailed data about a single variable star. In the upper left corner there are tables with coordinates, mean *I*-band magnitudes etc. In the center one can see a raw light curve in magnitude units and a 70 × 70 arcsec finding chart. The right part of the window displays photometric data points for the corresponding star. There is a selection of data between the DIA photometry in magnitude, the DIA difference flux and the OGLE photometry of the nearest star in *B*, *V* and *I*-band.